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Energy Procedia 37 (2013) 2746 – 2753
Energy Procedia

Investigating flexible carbon capture opportunities in the Australian electricity market

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Abstract

This paper investigates the use of a load-shifting strategy in combination with operating CO_2 capture at different capture rates for one electricity company in NSW, Australia. Real electricity dispatch data is used to analyse the operating patterns of the individual power plants owned by the electricity company. The analysis shows that when CO_2 is captured independently at each of the coal power plants without load-shifting, up to 11 Mt/yr of CO_2 can be avoided. The company's overall long run marginal cost (LRMC) for this scenario is approximately 115 A$/MWh. When the load-shifting strategy is employed, up to 20 Mt/yr of CO_2 can be avoided and the corresponding LRMC is approximately 110 A$/MWh.

Keywords: load-shifting, CO_2 capture, the NEM, black coal power plants

1. Introduction

1.1 Background

Climate change is believed to be one of the key challenges currently faced by the international community. Australia has set a target of between 5 % and 25 % reduction in greenhouse gas emissions by 2020 depending on global action and a further 80 % reduction by 2050 relative to levels in 2000 [1]. A carbon price of A$ 23 per tonne was introduced in July 2012. Economic modelling by the Australian Treasury shows that this carbon pricing scheme will transform the structure of the Australian energy market by shifting the generation mix towards cleaner energy, with gas generation increasing and traditional coal−fired generation declining. Carbon Capture and Storage (CCS) is one option under investigation for reducing CO_2 emissions at power plants during this transformation period.

One of the major obstacles faced by wide scale deployment of CCS is the cost of capturing CO_2 from dilute flue gas streams, such as those from coal fired power plants. Flexible operation of the capture facility at a power plant may reduce costs. Flexible operation can be achieved using measures such as

1876-6102
doi:10.1016/j.egypro.2013.06.159

adding a solvent storage tank, bypassing the capture facility for certain time periods or operating the capture facility at different levels according to electricity output requirements [2-4]. For example, in our previous work [5], we evaluated the opportunities for deploying flexible CO_2 capture at black coal fired power plants across the state of New South Wales (NSW) in Australia. This paper investigates the use of a load-shifting strategy in combination with operating the capture facilities at different capture rates for one electricity company in NSW. This company owns several power plants at different locations across the state with a total capacity of 4,320 MW.

2. Methodology

2.1 Economics assumptions

This study is presented in Australian dollars (A$). The real discount rate is 7 % with a project life of 25 years.

Power plant long run marginal cost (LRMC) and short run marginal cost (SRMC), as well as the cost of CO_2 avoided are estimated as shown in Equations 1 to 3:

$$\text{LRMC} = \frac{\text{Net Present Value of [Capex + Opex + Fuel cost + CO}_2\text{ emission cost]}}{\text{Net Present Value of [Electricity generated (MWh)]}} \tag{1}$$

$$\text{SRMC} = \frac{\text{Net Present Value of [Variable Opex + Fuel cost + CO}_2\text{ emission cost]}}{\text{Net Present Value of [Electricity generated (MWh)]}} \tag{2}$$

$$\text{CO}_2\text{ avoidance cost} = \frac{\text{Net Present Value of [Capex + Opex + Energy cost + CO}_2\text{ emission cost]}}{\text{Net Present Value of [CO}_2\text{ avoided (Mt/yr)]}} \tag{3}$$

The processing data and assumptions used in this study for the four coal power plants owned by the electricity company are shown in Table 1. The processing data presented are the actual operation conditions of the power plants as reported in publicly available sources, while the economic assumptions are those used by the CO2CRC [6]. Power plants A – D are all black coal fired power plants with subcritical boilers located in the state of NSW Australia.

Table 1 Characteristics of the individual power plants in the electricity company portfolio

Power plant	*A*	*B*	*C*	*D*	*Data sources*
Processing data					
Full commissioning date	1993	1978	1980	1969	[7]
Current registered maximum capacity (MW)	1400	1320	1000	600	[7]
CO_2 emission intensity before capture (t/MWh)	0.94	1.00	1.05	1.16	[8]
Thermal efficiency HHV (%)	37	35	33	31	[8]
Fuel cost ($/GJ)	1.8	1.75	1.8	1.75	[8]
Plant load-factor in 2010 (%)	88	62	50	12	[8]
Economic data (CO2CRC estimates)					
Power plant capital cost ($/kW)	1800	1800	1800	1800	[6]
Fixed opex (% of CAPEX)	4	4	4	4	[6]
Variable opex ($/MWh)	5	5	5	5	[6]
Short Run Marginal Cost ($/MWh)	23	24	25	26	
Long Run Marginal Cost ($/MWh)	49	61	71	225	

2.2 CO_2 capture evaluation

The analysis is carried out using a techno-economic model developed by UNSW for the CO2CRC. The model estimates the overall energy requirements and equipment sizes for power plant flue gas pretreatment, separation and CO_2 compression. The Mitsubishi KS1 solvent without heat integration is assumed to be used for the capture absorption process in this study. The energy required for capture (i.e. the steam required for solvent regeneration and the electricity for compression and pumping) is assumed to be parasitically extracted from the power plant.

Once capture is implemented with load-shifting, the power plant load-factor is assumed to be 85 %.

2.3 Power plant dispatch analysis without load-shifting

In Australia, electricity dispatch is driven by market conditions. Power plants do not always operate at full capacity. Thus, there is extra generation capacity that could be utilised for CCS. In this study, 2010 half-hour dispatch data is used to analyse power plant dispatch patterns. Half hour dispatch data were collected and plotted for the four coal-fired power plants. Figure 1 (a) shows the 2010 real dispatch curve for power plant A. It can be seen that the power plant dispatch is not constant but the load factor for this plant is high. Similarly, the dispatch was not constant for the other power plants in the portfolio, but their load factor varies as indicated in Table 1.

Analysis of CO_2 capture using real half-hour dispatch data is extremely difficult. To simplify the analysis, 7 – day generic dispatch curves are developed for each of the power plants. Each generic curve is created based on the average of the dispatch rate at the same time of the week over the entire year 2010. The generic dispatch curve for power plant A is shown in Figure 1 (b).

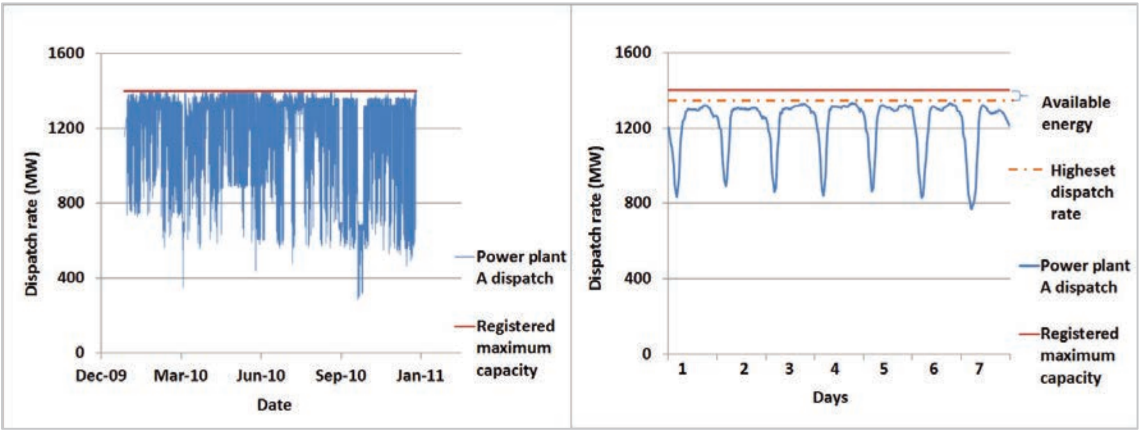


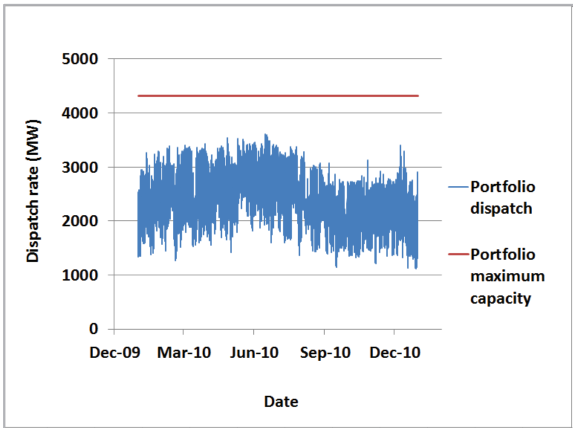
Figure 1 (a) Power plant A real dispatch in 2010 (b) Power plant A generic dispatch curve in 2010

Using the generic dispatch curves, we estimate the available energy for constant capture at each of the power plants. For simplicity, in this paper, the available energy is estimated as the difference between the maximum registered capacity and the peak dispatch rate on the generic dispatch curve.

2.4 Power plant dispatch analysis with load-shifting

Load-shifting refers to a strategy for managing the electricity output from multiple power plants. Within the context of CCS, load-shifting involves maximising the amount of CO_2 captured and minimising the cost of capture across the entire power plant portfolio while maintaining the total electricity output required to meet the electricity demand. This top-down load-shifting strategy is in contrast to a bottom-up approach for individual power plant where the CO_2 capture would be optimised at each power plant individually. The results of both options are presented in this paper.

Figure 2 (a) and 2 (b) show the real and generic dispatch curves for the portfolio in 2010 respectively. The real dispatch data is the sum of the dispatch data for the four power plants at each time, while the generic dispatch curve for the portfolio is generated in the same way as for the individual plants.



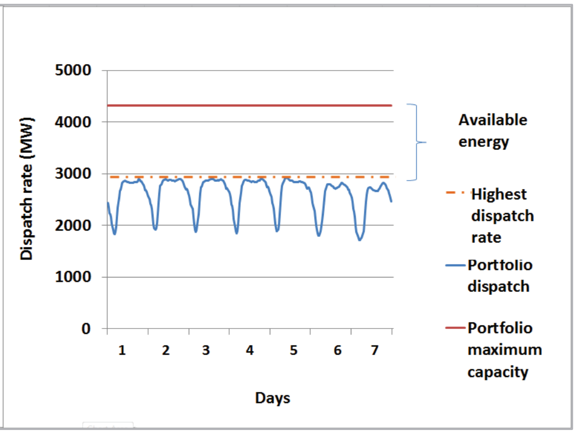


Figure 2 (a) Portfolio real dispatch data for 2010, (b) Portfolio generic dispatch curve for 2010

3. Results

3.1 CO_2 capture assessment without load-shifting

Table 2 shows the maximum available energy at each of the power plants and the corresponding amount of CO_2 that can be captured using this available energy without load-shifting. Power plant D has the most energy available for capture: about 510 MW. Power plants B and C also have a significant amount of energy available for capture, which is reflected in the high capture rates. In contrast power plant A has less than 70 MW available to power the capture system. The maximum amount of CO_2 that can be captured at all four power plants without load-shifting is about 17 Mt/yr. This corresponds to approximately 11 Mt/yr CO_2 avoided at an average cost across the portfolio of about 78 A$/t CO_2 avoided. The corresponding average LRMC for the portfolio is estimated to be about 114 A$/MWh and the SRMC is about 34 A$/MWh.

Table 2 CO_2 capture assessment without load-shifting

Power plant	*Available Energy (MW)*	*Capture rate (%)*	*Capture energy penalty (MW)*	*CO_2 captured (Mt/yr)*	*SRMC (A$/MWh)*	*LRMC (A$/MWh)*	*Avoidance cost (A$/t CO_2 avoided)*
A	67	15	65	1.6	24	62	149
B	363	80	327	8.0	36	96	70
C	408	90	257	6.3	40	110	70
D	512	90	190	1.0	45	275	85
Total	1350	59	691	16.9			
Portfolio cost					34	114	78

Power plants A, B, C and D have different SRMC with capture and LRMC with capture. The values range from 24 – 45 A$/MWh for the SRMC and 62 – 275 A$/MWh for the LRMC. The SRMC and LRMC are generally related to the thermal efficiency and load factors of the power plant; the thermal efficiency of the plants is also impacted by the CO_2 capture rate. Before capture, the SRMC of the four power plants range from 23 – 26 A$/MWh with a portfolio SRMC average of 24 A$/MWh. Power plant A is the most efficient plant with a thermal efficiency of 37 % (HHV) but it has similar variable opex and fuel costs to the other plants. Therefore power plant A has lower running costs than the other plants. As the thermal efficiency of the power plants decrease, the corresponding SRMC for the power plant increases. However, the difference between the SRMC for the different power plants before capture is not very large differing only by 1 – 2 A$/MWh.

In contrast, once capture is implemented, the range in SRMC values is much larger. For power plant A, which has a low rate of capture (at 20 %), the energy penalty is small (less than 70 MW from a total capacity of 1400 MW) and hence the change in thermal efficiency for the plant is also small. Therefore the difference in SRMC values for power plant A from before capture and after capture is about 1 A$/MWh. In addition, the LRMC increases by 13 A$/MWh due to the capital and operating costs for capture.

In comparison, implementing 90 % capture at power plant D increases the SRMC by 19 A$/MWh and LRMC by 49 A$/MWh. The high energy penalty for capture coupled with the very low efficiency and load factor for this plant, results in it having the largest increase in SRMC and LRMC. For power plants B and C, the SRMC and LRMC also increase by 12 – 15 A$/MWh and 35 – 39 A$/MWh, respectively. However, because these plants have moderate thermal efficiencies and load factors, the increase is not as significant as for power plant D.

The avoidance cost for power plant A is the highest in the portfolio at 149 A$/t. This is due to the low capture rate (15 %), which is constrained by the energy available for capture at this power plant. Power plant D also has relatively high avoidance cost because of its low load factor (12 %). Power plants B and C have the lowest avoidance cost (70 A$/t) because they both operate at a relatively constant level with a moderate load-factor of 50 – 60 %. Overall, without load-shifting, the portfolio captures about 60 % of the emissions at an overall avoidance cost of 78 A$/t CO_2 avoided.

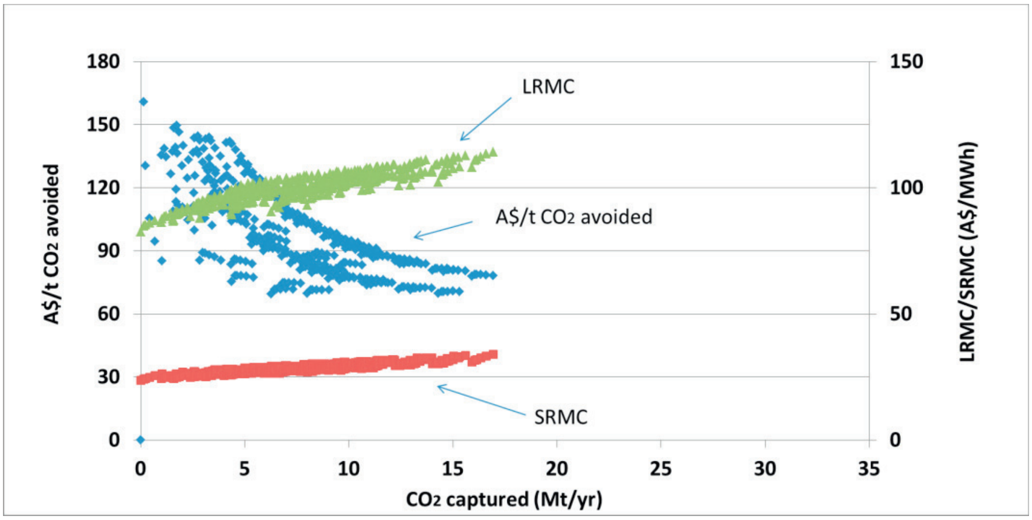


Figure 3 Results without load-shifting

It is also possible to capture less than the maximum amount of CO_2 at each power plant, thus using less than the total amount of available energy. As shown in Figure 3, this results in a range of amounts of CO_2 that can be captured across the portfolio with corresponding variable costs. The figure shows that increasing the amount of CO_2 captured results in an increase in both SRMC and LRMC, with the SRMC ranging from 25 – 35 A$/MWh and the LRMC ranging from about 80 – 115 A$/MWh. The avoidance cost generally decreases with increasing amounts of CO_2 captured, from 160 A$/t CO_2 avoided when less than 0.1 Mt/yr CO_2 is captured to 70 A$/t CO_2 avoided when almost 17 Mt/yr of CO_2 is captured. The figure also shows that there are fewer options available for capturing higher amounts of CO_2 than for capturing lower amounts of CO_2. For example, to capture 12 – 15 Mt/yr in this portfolio there are 45 combinations in comparison with 122 combinations that capture 6 – 9 Mt/yr. This is because all four power plants need to implement capture in order to capture high amounts of CO_2 across the portfolio; if less CO_2 needs to be captured, then only one, two or three power plants need to implement capture.

3.2 CO_2 capture assessment with load-shifting

As shown in Table 3, the energy available for powering CO_2 capture across the portfolio is about 1,400 MW. Table 3 shows the redistribution of the energy supply such that the amount of available energy at each power plant enables up to 90 % of the CO_2 generated at each power plant to be captured. This strategy increases the amount of CO_2 captured for the portfolio while still meeting the total electricity demand across the portfolio. If such a redistribution of energy supply is possible then up to 90 % of the CO_2 generated at each power plant could be captured while still meeting the total electricity demand across the portfolio. In fact, the amount of energy required for capture for this portfolio is approximately 1,200 MW, which is less than the amount of available energy across the portfolio. It should be noted that this theoretical redistribution of energy generation and capture assumes that all plants have a similar availability and are not constrained in terms of dispatch to the grid.

Table 3 CO_2 capture assessment with load-shifting

Power plant	*Available Energy (MW)*	*Capture rate (%)*	*Capture Energy penalty (MW)*	*CO_2 captured (Mt/yr)*	*SRMC (A$/MWh)*	*LRMC (A$/MWh)*	*Avoidance cost (A$/t avoided)*
A	>360	90	360	8.8	35	104	71
B	>361	90	361	8.9	36	107	70
C	>287	90	287	7.0	39	112	71
D	>191	90	191	4.7	42	119	73
Total	1400	90	1199	29.4			
Portfolio cost					37	109	71

Using load-shifting, the maximum amount of CO_2 that can be captured across the portfolio is about 30 Mt/yr at an average cost of about 71 A$/t CO_2 avoided within a small range of 70 – 73 A$/t CO_2 avoided. The corresponding SRMC and LRMC are estimated to be about 37 A$/MWh and 109 A$/MWh respectively. The SRMC and LRMC for the four power plants with load-shifting are 35 – 42 A$/MWh and 104 – 119 A$/MWh respectively. There is little variation in the SRMC and LRMC values and avoidance costs between the power plants as the capture rate and load factor for the four power plants are all about 85 % under the load-shifting strategy.

As for the results without load-shifting, it is also possible to capture less than 30 Mt/yr. Figure 4 shows similar trends to Figure 3 in that an increase in the amount of CO_2 captured results in increases in both the SRMC and LRMC while the range of avoidance costs narrows and approaches a lower boundary of about 70 A$/t avoided.

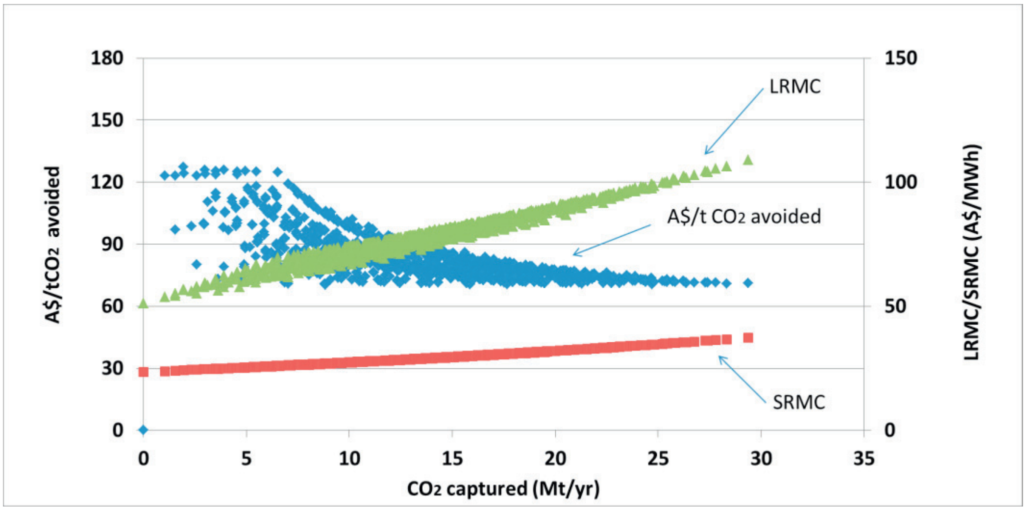


Figure 4 Results with load-shifting

3.3 Comparison of CO_2 capture strategies: with and without load-shifting

The results of this study show that the maximum amount of CO_2 that can be captured from the portfolio increases from approximately 17 Mt/yr to about 30 Mt/yr when load-shifting is employed. The overall capture rate increases from 60 % to 90 %. At this maximum capture rate, the SRMC and LRMC values for both strategies are very similar. Without loading shifting, the SRMC is 34 A$/MWh, and it is 37 A$/MWh with load-shifting. The SRMC is slightly higher with load-shifting because the less efficient power plants C and D are operating at a higher load factor thereby driving up the SRMC for the portfolio. The LRMC is about 114 A$/MWh without load-shifting, and 109 A$/MWh with load-shifting. For the two strategies, the avoidance cost decreases from 78 A$/t CO_2 avoided to 71 A$/t CO_2 avoided if load-shifting is employed.

At the individual power plant level, power plant A operates at very high load-factors without load-shifting providing up to 1,300 MW of electricity to the grid. Therefore only a small amount of energy is available for capture (about 67 MW) and as such only 15% of its emissions could be captured without load-shifting. In contrast, when load-shifting is applied, there is much more energy available for capture (an increase of more than 360 MW) and up to 90 % of the emissions across the entire portfolio might be able to be captured. Using load-shifting, some of the electricity output that was originally generated at power plant A is now generated at power plants B, C or D. In particular, power plant D is very under-utilised in the strategy without load-shifting; it had up to 512 MW of available energy but requires only 42 MW for capture. Once load-shifting is applied, all power plants are able to capture 90 % of the CO_2 emissions across the portfolio while still meeting the dispatch requirement to the grid.

However, capturing more CO_2 requires higher capital investment. This study found that when load-shifting is applied, the capital required for installation of the capture system is almost double that of the capital investment needed when no loading shifting is used. However, because load-shifting significantly increases the amount of CO_2 captured, the extra cost in capital is offset by the extra CO_2 avoided. Therefore the avoidance cost for the load-shifting strategy is lower.

4. Conclusion

This study shows that for an electricity company based in NSW, Australia, that owns four black coal power plants, there is the potential to apply 90 % CO_2 capture within the total available electricity capacity of all the plants while still meeting the commitment to supply electricity to the grid. The approach evaluated is a load-shifting strategy which shifts the electricity generation across the portfolio to maximise the energy available for capture at each of the power plants.

The results show that if CO_2 is captured independently at each of the coal power plants without load-shifting, up to 11 Mt/yr of CO_2 can be avoided. When the load-shifting strategy is applied, the amount of CO_2 that can be avoided is up to 20 Mt/yr, nearly a two-fold increase. The results also show that LRMC, SRMC and avoidance costs for both options are very similar at about 110 A$/MWh, 35 A$/MWh and 70 A$/t CO_2 avoided respectively. Therefore for this electricity company, load-shifting is a strategy that could be considered for maximising the amount of CO_2 captured at a similar unit cost to capturing at individual power plants without load-shifting.

This study used dispatch data for 2010, which may or may not be representative for the power plant operation in other years. Therefore, the results of this paper are only indicative. More investigation is warranted using data for other years and other companies to confirm the results. Further, the investigation focuses only on black coal power plants in Australia and the results may differ for other fuel sources.

5. Acknowledgments

The authors acknowledge the funding provided by the Australian Government through its CRC Program to support this CO2CRC research project. We thank Dr. Iain McGill for his comments and feedback.

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